

DEVELOPMENT AND TESTING OF BULK PHOTOCONDUCTIVE SWITCHES USED FOR ULTRA-WIDEBAND, HIGH-POWER MICROWAVE GENERATION

J.W. Burger, J.S.H. Schoenberg and J.S. Tyo
U.S. Air Force, Phillips Laboratory
Advanced Weapons and Survivability Directorate (PL/WSQW)
Kirtland AFB, NM 87117

M.D. Abdalla, S.M. Ahern and M.C. Skipper
Maxwell Technologies - Federal Division
Albuquerque Division
Albuquerque, NM 87119

W.R. Buchwald
U.S. Army, Army Research Laboratory
AMSRL-EP-ED
Ft. Monmouth, NJ 07703

***Abstract*—The Air Force Phillips Laboratory, in collaboration with the Army Research Laboratory (ARL), is developing lateral geometry, high-power photoconductive semiconductor switches (PCSS) for use in phased-array, ultra-wideband (UWB) sources. The current switch utilizes an opposed contact geometry with a 0.25 cm gap spacing and is an extension of previous work on 1.0 cm PCSS devices. This work presents the development and demonstration of the 0.25 cm PCSS under both ideal laboratory conditions and potential source conditions. The laboratory configuration consists of two high-bandwidth transmission lines connected with a PCSS. The potential source configuration consists of a vector-inversion pulse generator (Blumlein) commuted with a PCSS. Independent, low-jitter PCSS operation is demonstrated by series coupling two independent Blumleins into a common load. The 0.25 cm PCSS is shown to operate at 20 kV charge voltage, 65 ps rms switching jitter, less than 450 ps risetime and greater than 1 kHz pulse repetition rate (PRR) when triggered using a compact, high-power laser diode.**

I. Introduction

There is considerable demand within the technical community for sources which produce UWB radiation. The work presented here is centered on the development and testing of a PCSS in both a laboratory configuration and a potential source configuration. The laboratory configuration consists of a high-bandwidth source and load network which is used to measure the limits of PCSS performance. The potential source configuration consists of a compact UWB source/antenna module which can be duplicated and connected in a series/parallel array to produce high levels of radiated power. The primary module constraints, based on user requirements and the series/parallel interconnections in an array are; low system jitter, maximum power density, trigger isolation and fast output risetime.

The switch technology is a high-gain GaAs PCSS triggered with a compact (24.6 cm^3) laser diode system. This switch technology is used because of the low laser energy required to produce fast risetime, low jitter voltage pulses. This is attractive because the bulk of any source of this type is comprised of laser and pulsed power systems and any reduction in the size and mass of either system will yield a commensurate reduction in overall source size and mass. Although linear mode PCSS technology is a switching candidate, the current size and mass of the required laser systems prohibits their use in many applications. High-gain GaAs PCSS technology has been demonstrated in UWB high power microwave (HPM) sources^{1,2,3,4}. To date, risetimes as fast as 430 ps have been reported with switch hold-off fields of 67 kV/cm for a 1.5 cm, 100 kV switch². If sources are to produce higher radiated fields, some means, other than increasing the switch contact spacing must be developed, since increased switch gaps also increase the PCSS risetime and on-state switch potential. The opposed contact, lateral geometry PCSS is introduced

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE JUN 1997		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Development And Testing Of Bulk Photoconductive Switches Used For Ultra-Wideband, High-Power Microwave Generation				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Air Force, Phillips Laboratory Advanced Weapons and Survivability Directorate (PL/WSQW) Kirtland AFB, NM 87117				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.					
14. ABSTRACT The Air Force Phillips Laboratory, in collaboration with the Army Research Laboratory (ARL), is developing lateral geometry, high-power photoconductive semiconductor switches (PCSS) for use in phased-array, ultra-wideband (UWB) sources. The current switch utilizes an opposed contact geometry with a 0.25 cm gap spacing and is an extension of previous work on 1.0 cm PCSS devices. This work presents the development and demonstration of the 0.25 cm PCSS under both ideal laboratory conditions and potential source conditions. The laboratory configuration consists of two high-bandwidth transmission lines connected with a PCSS. The potential source configuration consists of a vector-inversion pulse generator (Blumlein) commuted with a PCSS. Independent lowjitter PCSS operation is demonstrated by series coupling two independent Blumleins into a common load. The 0.25 cm PCSS is shown to operate at 20 kV charge voltage, 65 ps rms switching jitter, less than 450 ps risetime and greater than 1 kHz pulse repetition rate (PRR) when triggered using a compact, high-power laser diode.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

here as a means of increasing the hold-off field while decreasing the switch contact spacing, thus reducing the PCSS risetime, jitter and on-state switch potential.

II. PCSS Design

The PL originally fabricated PCSS devices from 5.08 cm diameter, 0.5 mm thick GaAs wafers which had straight-edge metal contacts applied with a 1.0 cm spacing. The PL further developed the switch to incorporate a Rogowski profile contact geometry while maintaining the 1.0 cm minimum contact spacing⁵. The Rogowski profile reduces the electric field magnitude at the points where the GaAs-metal-dielectric interface intersects the wafer edge. This contact arrangement greatly increases the maximum voltage hold-off capability of the device. A need for smaller PCSS devices has led to the application of Rogowski profile contact geometries to small, rectangular GaAs wafers with a 0.25 cm minimum contact spacing. Although these 0.25 cm PCSS devices exhibited a roughly linear voltage hold-off capability scaling, the switch reliability and lifetime dropped significantly compared to the 1.0 cm PCSS. In an effort to increase the 0.25 cm PCSS reliability and lifetime, the contacts were revised to incorporate an "opposed contact" arrangement in which only one contact is applied to each wafer face, each at opposite ends of the switch⁶.

The PCSS was originally fabricated using only LEC material. A limited number of devices were fabricated from VGF material to determine the effect of reduced GaAs defect and impurity density. Experimental tests demonstrated that the LEC devices exhibited superior performance characteristics in on-state voltage drop, current risetime, device lifetime and required trigger energy. Therefore, all current PCSS devices are fabricated exclusively from LEC material.

The PCSS has been fabricated using two different metal contact compositions. The first (referred to as the standard contact) is a standard composition within the GaAs semiconductor industry for making electrical contact to GaAs. During lifetime tests of PCSS devices with standard contacts, the switches failed as a short circuit and the contacts showed signs of significant erosion. These observations led to concerns that the contact metals were being injected into the active switching region because of the high current densities associated with the filamentary current patterns. To minimize the contact erosion and switch failure, a refractory metal contact composition (referred to as the refractory contact) was specified. Initial lifetime tests indicate that the refractory contact performs as well as the standard contact and exhibits significantly less erosion.

III. Experimental Support Equipment

In both the experimental and source PCSS tests, the same pulsed power source is used. A 1,000 μF capacitor is discharged into the primary of a 100:1 pulse transformer using a high-current, push-pull MOSFET switching circuit. The secondary of the pulse transformer delivers a 40 μs risetime charging voltage to the pulse forming network (PFN). The output of the transformer secondary is controlled by the charge voltage on the 1,000 μF capacitor and the width of the voltage pulse delivered to the transformer primary by the MOSFET circuit. This circuit was chosen because it has minimal stored energy in the transformer and allows positive control of the voltage and current applied to the PCSS after switching has occurred.

Previously, PCSS devices have been triggered using mode-locked Nd:YAG lasers, frequency doubled Nd:YAG lasers and Nd:YAG-pumped Ti:Sapphire lasers. The current devices are triggered using a compact, high-power laser diode. The diode is a Laser Diodes, Inc., model LD-230. The driver was developed in-house and utilizes a high-current capable MOSFET to discharge a low-inductance capacitor into the laser diode. The low-inductance capacitor has a capacitance of 500 pF and is charged to 500 VDC. A novel circuit arrangement topology allows the MOSFET to produce current risetimes of approximately 1 ns into the laser diode. The LD-230 optical output has a 200 ps 10% - 70% risetime, 20 ns pulse width and 600 W peak output power.

For laboratory level testing, the PCSS is series connected between two coaxial transmission lines of equal impedance; one transmission line functions as the source PFN, the other functions as the load. The transmission lines are enclosed in a sealed SF_6 pressure containment vessel. The source and load transmission lines have a characteristic impedance of 75 Ω . The load transmission line is terminated with a high bandwidth, 75 Ω resistor network. The source line is 30.5 cm long and produces a 2 ns output voltage pulse through the PCSS and into the

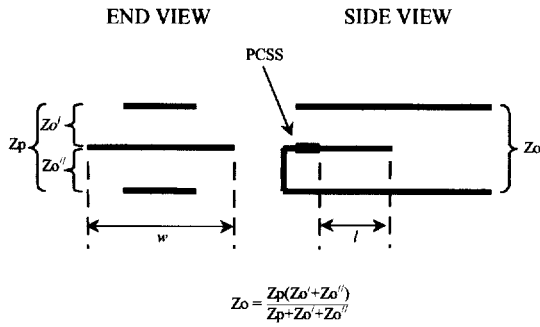


Figure 1. Blumlein impedances.

load. The load line is 122 cm long and has a high-bandwidth capacitive probe installed on the ground plane at the mid-point. A sapphire laser/view port is installed in the outer containment vessel wall.

IV. Source Configuration

A triaxial parallel-plate Blumlein is used as the source PFN, as shown in Fig. 1. The center conductor is charged to a voltage V_c and commuted to an exterior conductor with the PCSS. The Blumlein generates a unipolar voltage pulse which is guided by a 2 ns isolation transmission line to a TEM horn antenna. The Blumlein PFN, isolation transmission line, and antenna have a characteristic impedance of $Z_o = 190 \Omega$. The balanced, parallel-plate source requires no geometry converter, and allows for direct connection to the TEM horn antenna with minimum pulse dispersion.

The output voltage amplitude (V_o) of a Blumlein is sensitive to the ratio Z_p/Z_o , where Z_p is the parasitic impedance. The parasitic impedance is a result of those electric field lines which directly connect the exterior Blumlein conductors without coupling through the center conductor. Z_o' and Z_o'' are illustrated in Fig. 1. The total Blumlein impedance is given as

$$Z_o = \frac{Z_p(Z_o' + Z_o'')}{Z_p + Z_o' + Z_o''}$$

where Z' and Z'' are the impedances of the two transmission lines comprising the Blumlein. For the case where the center conductor is centrally located between the exterior conductors, $Z_o' = Z_o''$. As Z_p/Z_o approaches unity, V_o approaches zero. This ratio represents the case in which the Blumlein center conductor is infinitely narrow compared to the exterior conductor widths. As Z_p/Z_o approaches infinity, V_o approaches $-V_c$. This ratio represents the case where the Blumlein center conductor is infinitely wide compared to the exterior conductor widths. In addition, as the conductors to which the PCSS connects become wide compared to the 1.27 cm width of the 0.25 cm PCSS contact, the pulse wave front may disperse, increasing its rise time. Therefore, an acceptable balance between the amplitude and spectral content of the output pulse must be determined.

The electrostatic software package Electro⁷ is used to numerically determine the Blumlein impedances. Electro is a two-dimensional static boundary-element-method code which is used to numerically solve for the Blumlein capacitance matrix. Both Z_p and Z_o are then determined from the capacitance matrix and inserted into a Pspice⁸ model of the Blumlein. The model is then used to determine the amplitude variation of V_o/V_c for different values of w , the Blumlein center conductor width, as shown in Fig. 2. Fig. 3 illustrates the variation of Z_p and Z_o as a function of w . Note that as w increases, there is a small decrease in Z_o and a large increase in Z_p .

Laboratory experiments are used to verify changes in V_o/V_c and rise time as a function of w . The Blumlein used for experiments consists of exterior conductors which are 1.0 cm wide and have a center-to-center spacing of 1.8 cm. The Blumlein center conductor is located centrally between the exterior conductors, and all conductors are fabricated from 6061-T6 aluminum. The Blumlein is assembled using nylon 2-56 screws. The nylon screws are verified to perturb the Blumlein impedance (Z_o) by less than 1% using the Tektronix 11801 TDR. Three center

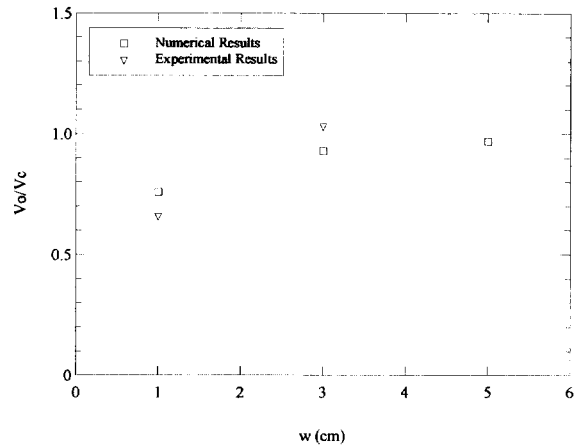


Figure 2. V_o/V_c as a function of w .

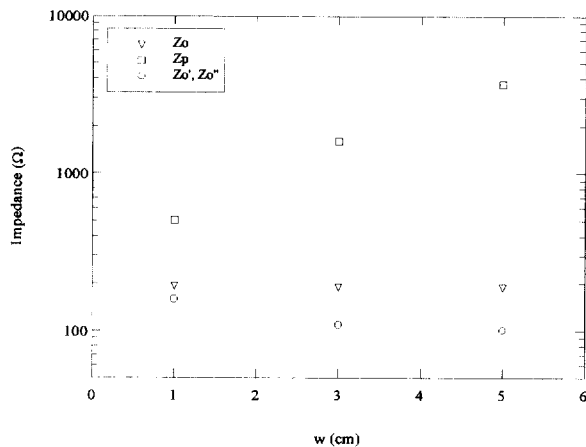


Figure 3. Z_o , Z_p , Z_o' and Z_o'' as a function of w .

of curvature equal to half their thickness. A calibrated

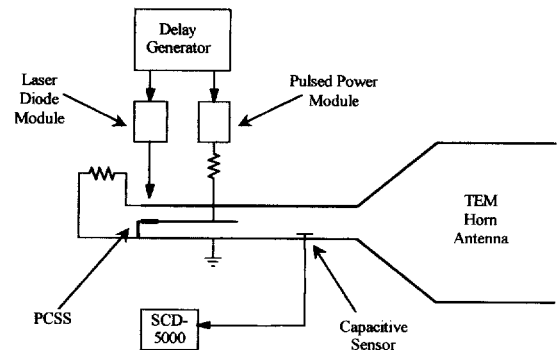


Figure 4. Source configuration.

conductor widths are modeled; 1.0, 3.0, and 5.0 cm. All conductors are 1.59 mm thick, and have an edge radius

The 0.25 cm PCSS is installed between the center and bottom conductors of the Blumlein, as shown in Fig. 4. A laser entry hole is incorporated into the upper Blumlein conductor above the PCSS. A 30 kΩ resistor is used to tie the exterior Blumlein conductors to a common ground potential during the charge phase. The center conductor is charged to $V_c = 13$ kV, and the PCSS is activated using the laser diode module. The entire Blumlein structure is enclosed in an acrylic tube filled with SF_6 at 1 atm. The tube endplates are also fabricated of acrylic, and the output endplate incorporates a constant impedance feedthrough for connection to the isolation transmission line and TEM horn antenna.

A TEM-horn transmission-line antenna with highly directional properties may be designed such that the effective height, risetime, and clear time can be chosen independently⁹. The antenna output is designed to have 30.0 cm X 30.0 cm cross sectional dimensions (178 Ω) for convenient stacking into a multi-element array and as a close match to the 190 Ω source impedance. The antenna risetime is chosen as 100 ps to minimally perturb the radiated waveform. The antenna is designed as a linearly tapered horn with length = 47.0 cm and throat angle (θ) = 17.7°. A 30 cm parallel-plate extension is added to the antenna output to provide a 2 ns antenna clear-time and to provide a late-time margin for the source pulse width.

V. Experimental Results

The 0.25 cm opposed-contact PCSS is tested in the 75 Ω transmission line test fixture described above using the laser diode module as the trigger source. The 0.25 cm PCSS exhibits a 23 kV maximum hold-off potential and a 20 kV working potential, producing an 80 kV/cm working field across the gap. The measured switch rise time in this configuration is 420 ps. A maximum lifetime of 5×10^4 has been achieved with the 0.25 cm PCSS operated at a 1 kHz PRR and a charge voltage of 20 kV. The on-state potential across the switch is 1 kV, and is independent of the switched current. The switching jitter and delay with respect to laser illumination are strong functions of the applied voltage, as shown in Figs. 5 and 6. A switching jitter of 65 ps rms is measured at 20 kV, and increases to 2.1 ns at 10 kV. The measured switching delay is minimum at 20 kV, and rises to 22 ns at 10 kV. The switching delay values are referenced with respect to the measured delay at 20 kV.

The Blumlein has been tested with four different center conductors. Each center conductor width ($w = 1.0$ and 3.0 cm) was tested at two different lengths ($l = 7.6$ and 22.9 cm). Center conductor widths of 1.0 and 3.0 cm correspond to a Z_p of 1,594 and 503 Ω, respectively. The experimental results of these tests are shown in Figs. 7 and 8. The rise times for all center conductor tests are measured to be 420 ps, indicating that there is little difference in wavefront dispersion for the two different center conductor widths. Center conductor lengths of 7.6 and 22.9 cm correspond to a pulsewidth of 0.9 and 1.8 ns FWHM, respectively. The numerical and experimental values of V_o/V_c are given in Fig. 2, which clearly show that the voltage transfer efficiency improves with an increase in w .

VI. Conclusions

An ultra-wideband pulse generator has been developed incorporating a reduced size, high-gain, GaAs PCSS. The switching jitter is as low as 65 ps rms, and is strongly dependent on the applied voltage when triggered with the compact laser diode module. Future switch development will yield PCSS devices capable of sustaining higher fields, thereby reducing switching jitter and risetime. The revised PCSS geometry is easily integrated into compact, parallel-plate Blumlein sources used to drive a TEM horn antenna. Theory and experimental validation show that the Blumlein voltage transfer efficiency is improved by increasing the center conductor width with respect to the width of the exterior conductors.

References

- ¹ F. J. Zutavern, G. M. Loubriel, W. D. Helgeson, W. M. O'Malley, M. H. Ruebush, H. P. Hjalmarson, and A. G. Baca, "Optically-activated GaAs switches for compact accelerators and short pulse sensors," in *Proc. 1996 22nd IEEE Int. Power Modulator Symp.*, pp. 31-34.
- ² G. M. Loubriel, J. F. Aurand, M. T. Buttram, F. J. Zutavern, W. D. Helgeson, W. M. O'Malley, and D. J. Brown, "High gain GaAs photoconductive semiconductor switches for ground penetrating radar," in *Proc. 1996 22nd IEEE Int. Power Modulator Symp.*, pp. 165-168.
- ³ D. C. Stoudt, "Demonstration of a frequency-agile RF source configuration using bistable optically controlled semiconductor switches (BOSS)," in *Proc. 10th IEEE Int. Pulsed Power Conf.*, 1995, pp. 360-365.
- ⁴ R. L. Druce, M. D. Pocha, K. L. Griffin, J. M. Stein, B. James, and J. O'Bannon, "Wideband microwave generators with GaAs photoconductive switches," in *Proc. 8th IEEE Int. Pulsed Power Conf.*, R. White and K. Prestwich, Eds, 1991, pp. 114-117.
- ⁵ J.S. Choy, J.P. Hull, M.D. Abdalla, M.C. Skipper, "Salient trigger parameters for inducing lock-on in gallium arsenide, semiconductor switches," in *Proc. 9th IEEE Int. Pulsed Power Conf.*, 1993, pp. 684-687.
- ⁶ W. R. Buchwald, A. Balekdjian, J. Conrad, J. W. Burger, J. S. H. Schoenberg, J. S. Tyo, M. D. Abdalla, M. C. Skipper, S. M. Ahern, "Fabrication and design issues of bulk photoconductive switches used for ultra-wideband, high-power microwave generation," To be published in *Proc. 11th IEEE Int. Pulsed Power Conf.*, 1997.
- ⁷ Electro electric field solver, Integrated Engineering Software, Inc., Winnipeg, Canada, 1985.
- ⁸ PSpice circuit analysis, MicroSim Corp., Irvine, CA, July, 1990.
- ⁹ C. J. Buchenaur and R. Marek, "Antennas and electric field sensors for time domain measurements: An experimental investigation," in *Ultrawideband, Short-Pulse Electromagnetics 2*. New York: Plenum, 1995, pp. 197-208.